NASA'S DEEP SPACE TELECOMMUNICATIONS ROADMAP

Charles D. Edwards, Jr., Charles T. Stelzried, Leslie J. Deutsch, and Laif Swanson

Telecommunications and Mission Operations Directorate
Jet Propulsion Laboratory
M/S 303-402
Oak Grove Drive
Pasadena, CA 91109
chad.edwards@jpl.nasa.gov

ABSTRACT

With the advent of faster, cheaper planetary missions, the coming decade promises a significant growth in the number of missions that will be simultaneously supported by NASA's Deep Space Network (DSN). In addition, new types of missions will stretch our deep space communications capabilities. Ambitious outer planet missions, with extremely tenuous communications links due to their great distance, and data-intensive orbiter or *in situ* missions incorporating high-bandwidth science instruments, will demand improved telecommunications capabilities. Ultimately, our ability to create a virtual presence throughout the solar system will be directly linked to our overall deep space telecommunications capacity. The Telecommunications and Mission Operations Directorate at the Jet Propulsion Laboratory, which operates NASA's Deep Space Network, has developed a roadmap for deep space telecommunications through the year 2010 which meets these challenges. Key aspects of this roadmap are: 1) a move to efficient, standard communications services; 2) development of an end-to-end flight-ground communications architecture and co-ordination of flight and ground technology developments; 3) rapid infusion of Ka-band and optical communications technologies into the DSN and into future spacecraft. This paper will present this roadmap, describe how it will support an increasing mission set while also providing significantly increased science data return, summarize the current state of key Ka-band and optical communications technologies, and identify critical path items in terms of technology developments, demonstrations, and mission users.

1. INTRODUCTION

One of the primary goals identified within NASA's most recent Strategic Plan [NASA, 1998] is "to establish a virtual presence throughout the solar system." The fidelity of this virtual presence will in large part be defined by the communications bandwidth that we can provide between our robotic spacecraft and the scientists, engineers, and public who interact with them here from Earth. Consistent with this, the National Research Council recently identified "wideband, high data-rate communications over planetary distances" as one of six key technoligies with the potential to "lower the cost and improve the performance of existing space activities and enable new ones" [National Research Council, 1998]. TMOD recently carried out a study to examine our deep space communications capability in a rigorous, quantitative way and to identify the most cost-effective options for future growth.

Section 2 of this paper will describe the challenge TMOD faces as we move to an era of far more frequent launches. Section 3 will then present TMOD's strategy for responding to this challenge. In particular, we will focus on how TMOD is applying new technology developments in Ka-band and optical communications to provide extremely cost-effective growth in our deep space communications capability. Finally, in Section 4 we will summarize what we have learned in this study, and what recommendations we are making regarding the future of deep space communications.

2. TELECOMMUNICATIONS CHALLENGES

One of the great dividends of the "faster, better, cheaper" NASA is the agency's ability to launch far more frequent new missions. We have successfully evolved in a few short years from an era of infrequent "flagship" missions to frequently launched missions and multi-mission programs such as Discovery, Mars, and Outer Planets. Based on a conservative forecast of future missions, TMOD anticipates a significant increase in the number of missions supported, from a current level of roughly 25 simultaneous missions up to roughly 35 simultaneous missions in five years. (A more aggressive forecast, based on the NASA Administrator's goal of a launch every month, would lead to over 50 simultaneous missions.) This increasing mission set will stress the capacity of TMOD's Deep Space Network.

In addition to the sheer number of missions, the types of missions NASA will fly will also stretch our deep space communications capabilities. Outer planet missions play a key role in NASA's planetary roadmap, and because communications performance scales inversely as the square of distance, communicating from Pluto or Neptune will be 100 times more difficult than for a Mars mission (and 10 *billion* times more difficult than for a typical communications link between a commercial geostationary satellite and the ground!) Also, future missions will tend to be data-intensive, as we move from an era of fly-by missions to long-duration orbiters and *in situ* investigations, with spacecraft incorporating high-bandwidth instruments such as multispectral imagers.

This increasing mission set can not be accomodated with the current DSN ground network, based on today's mission operations concept. A loading study has been performed based on today's mission support scenario: three 8-hr tracking passes per week during cruise and daily 10-hr tracking passes during prime mission phase (e.g., encounter). Based on these assumptions, even the conservative future mission set leads to a 60% oversubscription of DSN antenna capacity by the year 2005.

How will JPL and NASA respond to this challenge? The answer is threefold. First, we must begin to look at the telecommunication link from an end-to-end perspective, starting from the spacecraft instruments all the way through to the project scientists and engineers on the ground. JPL has taken an important step by creating the Telecommunications and Mission Operations Directorate with just this goal in mind. TMOD has the responsibility to define the overall end-to-end architecture for deep space communications and mission operations, and to create a co-ordinated technology development roadmap that responds to the needs of the anticipated future mission set. The model of this end-to-end architecture, shown in Figure 1, is a "solar system wide area network", much like the Internet but extending from Earth out to all our planetary spacecraft, providing seamless connectivity between scientists and their spacecraft instruments.

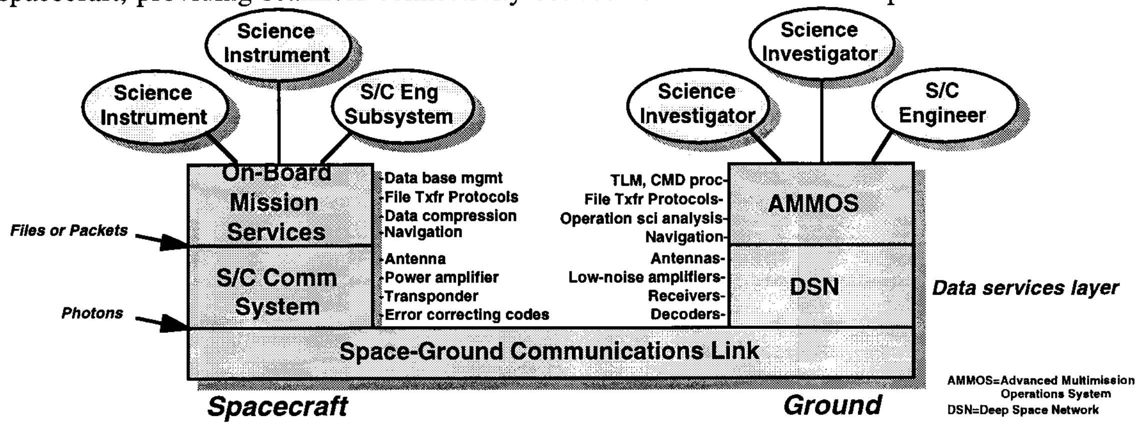

Figure 1: Layered flight-ground model of deep space telecommunications and mission operations

Second, TMOD and its customers must move to a new paradigm in which TMOD provides standard, cost-effective, high-level services. An important example of this is how we think of downlink telemetry. In the past, missions have requested hours of DSN antenna time and dealt with their telemetry at the bit level. In the future, missions will request file transfers, analogous to the FTP services used on the Internet, with robust space communications protocols handling any needed retransmisisons, ensuring that all data are successfully delivered to the project. The end-to-end, flight-ground telecommunications system will be engineered to deliver this service reliably and efficiently; for instance, space link protocols will be designed to handle packet acknowledgements and request re-transmission of unreceived packets to ensure reliable file transfer without the customer needing to worry about bit-level details.

Third, and perhaps most importantly, rapid infusion of new technology will be key to meeting NASA's deep space communications challenge. The quantity, quality, and cost of our deep space communications capabilities are highly dependent on the state of our technology. And advances in component technology will offer opportunities for significant, cost-effective capability growth. Consider this analogy: every few years, advances in digital processing technology lead to big performance increases in personal computer modems, allowing you to - at low cost - significantly increase the bandwidth with which your home computer can interact with the Internet. In a similar way, key technology developments are offering NASA the opportunity to cost-effectively increase its deep space communications capabilities. In particular, Ka-band and optical communications technologies have the potential to provide an order of magnitude increase in performance by the year 2010.

3. TECHNOLOGY ROADMAP

3.1 TELECOMMUNICATIONS METRICS

To speak quantitatively about communications performance, we need to define some useful metrics. In the past, we have tended to think in terms of available antenna hours, and that is an easy metric to understand. To increase this metric, you can build new antennas or try to increase the utilitzation of the antennas you already have by reducing set-up times.

As we move towards a service paradigm, and think in terms of file transfers instead of antenna hours, we need to characterize the data volume that can be downlinked into any given DSN antenna in a given pass length. To be quantitative here, we need to define what is at the other end of the link. And so we will define a "reference spacecraft" at Jupiter distance: we normalize the spacecraft to have an RF output power of 10 W and an antenna diameter of 1.4 m (which, for a 50% efficient antenna, provides the equivalent of a 1m antenna). This is characteristic of the types of communications systems that the mass-, power-, and volume-constrained missions of the future are baselining. To extend this definition to the optical domain, we postulate a spacecraft system consisting of a 30 cm telescope aperture and a 3 W laser output, corresdponding to the specifications of the optical transceiver being built within the NASA Advanced Space System Development Program (also known as the X2000 program). With this definition, we can speak quantitatively about the data rate that this reference spacecraft can downlink into any given ground antenna (RF) or telescope (optical).

Finally, with this single-aperture definition in place, we can also talk about the aggregate capacity for the entire ground network, by adding up the downlink rates for all the antennas/telescopes in the DSN. In effect, this corresponds to the aggregate bandwidth that the DSN could supply to an ensemble of "reference" spacecraft at Jupiter distances. For reference, in terms of this metric, today's DSN provides an aggregate capacity of only 20 kbps at S-band (2.3 GHz), 230 kbps at X-band (8.4 GHz), and no operational capility yet at Ka-band (32 GHz) and optical (1.06 microns).

3.2 BASELINE RF SYSTEM IMPROVEMENTS

A number of planned improvements are expected to lead to significant improvements in the DSN's current X-band telecommunciations capability. These include:

- DSN Ground Station Automation: TMOD is initiating a comprehensive network upgrade which will modernize and simplify DSN subsystems, increase use of standard commercial systems wherever applicable, and significantly increase the level of system operation. In addition to reducing operations costs, this work will also lead to increased antenna utilization due to a reduction in the pre-calibration/post-calibration time required for each tracking pass, from a current value of over one hour down to a goal of five minutes. Reducing this pre-cal time is especially important as we move towards more short tracking passes. These network improvements are planned to be completed in the 2001 time frame.
- Improved X-band Diplexing Feed Systems: A new RF feed system technology allows diplexed (two-way) communications through a single RF feed without need for a lossy microwave diplexer, resulting in a substantial reduction in the operational system noise temperature.

Turbo Codes: A new class of error-correcting codes [Divsalar and Pollara, 1995] is being developed, offering 0.7 dB advantage over the current Reed-Solomon/convolutional (15,1/6) concatenated code. NASA's next-generation deep space transponder, the Spacecraft Transponding Modem, a prototype of which will be completed by 2001, will support this new code, and implementation of turbo decoders in the DSN is planned by 2003.

3.3 Ka-BAND COMMUNICATIONS ROADMAP

The DSN currently supports deep space communications at S-band (2.3 GHz) and X-band (8.4 GHz). While the baseline RF improvements mentioned above will increase DSN capacity, they are insufficient to meet the anticipated needs of the future mission set. To achieve more significant increase in deep space capacity, we must either build additional S/X-band antennas or move to higher communications frequencies.

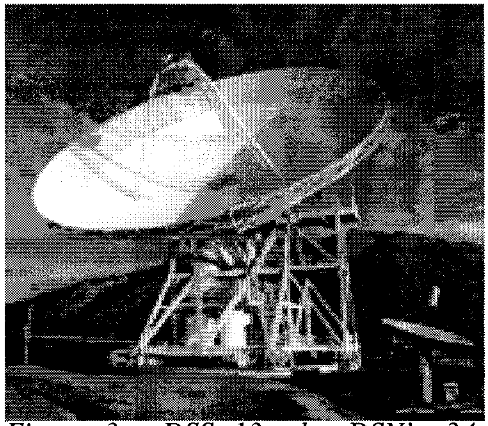

Figure 3: DSS 13, the DSN's 34m Research and Development Antenna

The next frequency allocation for deep space communications above X-band is Ka-band (32 GHz). Ka-band offers roughly a four-fold performance advantage over X-band for high-rate downlinks, due to the increased directivity of the downlink beam as one moves to shorter wavelengths. This opens up an interesting trade space for future Ka-band missions: with the same antenna size and RF power, and the same amount of tracking time, a Ka-band mission can return four times more data than a comparable X-band mission. Alternatively, total data return can be kept constant while reducing DSN tracking time by a factor of four (an important consideration as we enter an era of full cost accounting in which missions will pay for tracking services.) The trade space also includes the spacecraft: instead of increasing data return or reducing tracking time, missions can use the performance gain to reduce spacecraft antenna area or RF power by a factor of four. Each mission will be able to optimize these trades to best benefit from Ka-band's fourfold advantage. For the purpose of this analysis, we make the following assumption: future missions, starting in 2005, will utilize Ka-band to allow a 50% reduction in tracking time while also achieving a factor-of-two increase in overall science data return. In this way, Ka-band provides a "win-win" solution that copes with the increasing number of missions that the DSN must support while also providing increased science return to each individual mission.

A development roadmap, including co-ordinated flight and ground technology developments, has been established to support the use of Ka-band in this time frame. Key aspects of this roadmap, shown in Figure 2, include:

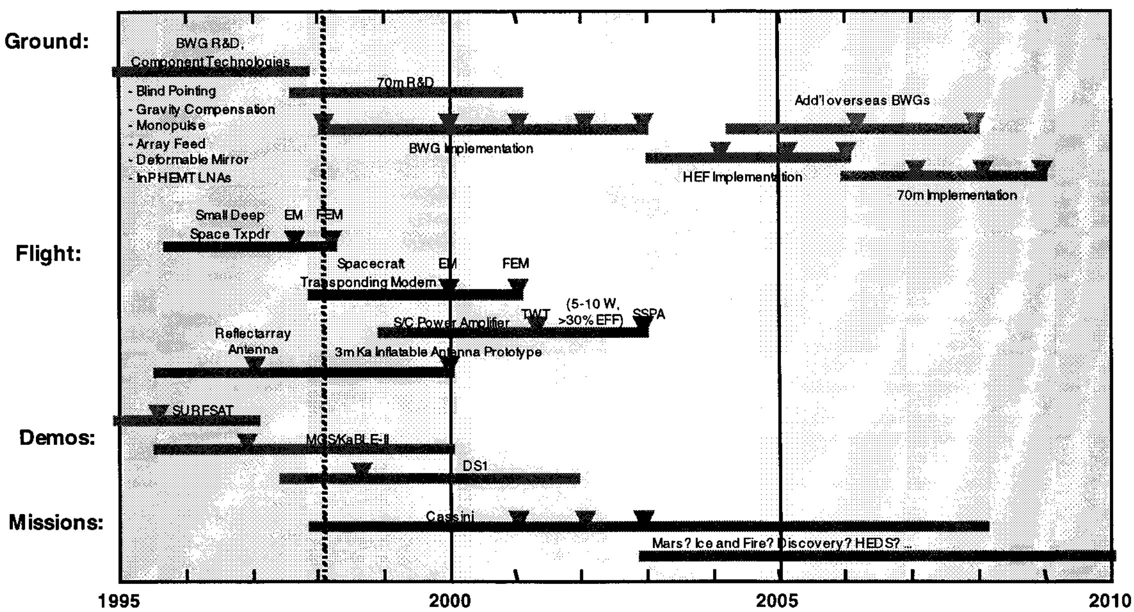

Figure 2: Ka-band deep space telecommunications roadmap

- *Rapid deployment of Ka-band receive capabilities in the DSN:* DSS 13, the DSN's research and development antenna shown in Figure 3, has served as a testbed for developing Ka-band ground technologies [Edwards, et al., 1997, Morabito, 1996]. DSS 13 currently supports Ka-band, and the first operational Ka-band capability is just now coming on line at DSS 25, a 34m beam waveguide (BWG) antenna at Goldstone's Deep Space Communications Complex. The roadmap calls for adding Ka-band to all five 34m BWG antennas by 2003, followed by implementation on the three 34m high-efficiency (HEF) antennas by 2006, and finally on the three 70m antennas by 2009. Making the 70m antennas perform well at the 1 cm wavelength of Ka-band will be technically challenging, as the primary antenna surface deforms by a significant fraction of this wavelength due to changing gravitational loads as the antennas tracks a target in elevation. The TMOD Technology Program is pursuing two candidate technologies to compensate for these antenna deformations (Figure 4). In one approach, a small deformable mirror in front of the 70m RF feed is programmed to compensate for the wavefront distortion caused by the primary surface deformation [Rengarajan, et al., 1998]; this approach can be thought of as the RF equivalent of the adaptive optics systems used in state-of-the-art astronomical telescopes. In the other approach, a cluster of seven feeds collects the defocused Ka-band signal and adaptively recombines it electronically to achieve this compensation [Vilnrotter and Iijima, 1996].

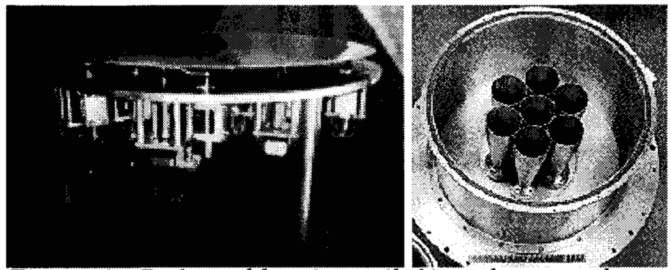

Figure 4: Deformable mirror (left) and seven-element array feed (right), two candidate technologies for achieving high aperture efficiency at 32 GHz on the DSN's 70m antennas.

- *Availability of efficient, low-cost, low power, Ka-band flight components:* Key elements of the spacecraft radio system include the transponder, the power amplifier, and the high-gain antenna.
  - The new Small Deep Space Transponder (SDST), developed by Motorola under contract to NASA, will fly on the New Millennium Deep Space 1 mission in 1998. This transponder for the first time provides both X-band and Ka-band downlink exciter options, in addition to its X-band uplink receive capability. And NASA's next-generation deep space transponder, called the Spacecraft Transponding Modem (STM) and targeted for prototype delivery in 2001 and flight application starting in 2003, will augment the SDST functionality with support of turbo codes, spacecraft timekeeping services, frame level interface with the flight computer, all in a smaller, lighter, lower-power, and lower-cost package [Riley, et al., 1996].
  - Ka-band power amplifiers are currently a key missing element in the overall Ka-band system. While X-band solid state power amplifiers (SSPAs) currently offer 30% DC-to-RF power efficiency and output power in the 5-10 W range, Ka-band SSPAs currently offer only about 10-15% power efficiency with output power in the 1-3 W range. To address this, TMOD is currently establishing plans for the development of a 32 GHz Traveling Wave Tube Amplifier (TWTA), with delivery of a prototype in 2000. Performance goals for this device are 40% power efficiency, 10 W RF output, and 1.5 kg total mass. Based on the extensive and highly reliable use of TWTAs in commercial space applications at other microwave frequencies, this appears to be a low-risk path to a near-term Ka-band amplifier with excellent efficiency. Longer-term research on quasi-optic Ka-band SSPA amplfiers is aimed at similar power and efficiency specifications, but at lower mass and cost.

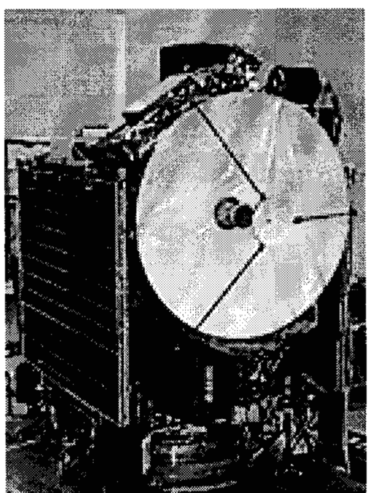

Figure 5: The Mars Global Surveyor spacecraft, including the Ka-band Link Experiment (KaBLE-II).

  - Antennas tend to vary significantly from mission to mission, depending on specific telecom needs, spacecraft design issues, and launch vehicle constraints. The Mars Global Surveyor spacecraft is flying a dual frequency, Cassagrain X/Ka-band high-gain antenna. Other novel designs with lower mass or stowed volume are also being investigated at Ka-band, including fixed and inflatable reflectarray antennas.

- *Flight demonstrations:* Actual flight demonstrations are critical for validating Ka-band flight and ground components, assessing the increased effects of weather on the Ka-band link, and giving future missions confidence in moving to Ka-band. The Mars Observer spacecraft carried the first deep space experimental Ka-band downlink in 1992. Initial tests were successful [Rebold, et al., 1994], but the loss of the spacecraft limited the experience gained. More recently, in 1996 the Mars Global Surveyor spacecraft (Figure 5) carried a second Ka-band flight experiment that included a 1 W Ka-band SSPA with 11% power efficiency and a dual frequency X/Ka-band high-gain antenna [Butman, et al., 1997]. And later this year, the New Millennium DS1 mission will demonstrate Ka-band downlinks with the Small Deep Space Transponder and a 2.5 W, 15% efficient Ka-band SSPA.

- *Flight mission applications:* Cassini is the first mission that is flying Ka-band as an operational part of their prime mission. Cassini will use Ka-band uplinks and downlinks, not for telemetry but rather for high-precision radio science experiments. A single Goldstone 34m BWG antenna will support these Ka-band links for Cassini, providing a benchmark on ground station performance and valuable experience in working at Ka-band. A wide array of missions in the 2003-and-beyond time frame are now looking at Ka-band as an option in their mission designs. Potential Ka-band users include missions in the Mars Surveyor Program, the Outer Planets program (including Europa Orbiter, Pluto Express, and Solar Probe), the new Millennium program, and the yet-to-be-named missions in the Discovery program. TMOD will be working with these future missions to cooperatively examine the end-to-end telecommunications link issues and the potential benefits of Ka-band for these missions.

3.4 OPTICAL COMMUNICATIONS ROADMAP

Looking beyond Ka-band, optical communications holds the promise of even higher telecommunications performance, once again due to much higher directivity of the spacecraft's laser signal towards Earth. (Whereas a 1m spacecraft RF antenna generates a diffraction-limited beamwidth of about 30 mrad at X-band and 10 mrad at Ka-band, a 10 cm telescope generates an optical beamwidth of 10 μrad or less.) Though in its early stages, the development of optical communications for deep space has already accomplished several important milestones. In 1992, the Galileo Optical Pointing Experiment (GOPEX) successfully demonstrated transmission of ground-based laser signals up to the Galileo spacecraft [Wilson and Lesh, 1993]. And in 1995, JPL and Japan's Communications Research Laboratory collaborated to demonstrate bi-directional optical communications at rates of up to 1 Mbps between JPL's Table Mountain Facility and the Japanese ETS VI spacecraft (see Figure 6) [Wilson, et al., 1997]. On the flight side, NASA's Crosscutting Technology program has sponsored the development at JPL of an Optical Communications Demonstrator (OCD), shown in Figure 7. The OCD is a prototype optical communications terminal applicable to Gbps near-Earth missions as well as lower rate deep space missions [Yan, et al., 1997].

Figure 6: Multi-beam laser uplink from Table Mountain 0.6m Telescope to the ETS-VI spacecraft during the Ground to Orbit Lasercom Demo (GOLD)

As with the RF domain, TMOD has established a coordinated flight-ground roadmap of technology development leading to a deep space optical communications capability, as shown in Figure 8.

- *Deployment of optical ground stations:* TMOD has initiated in 1998 the development of an Optical Communications Telescope Laboratory (OCTL), a 1-meter optical telescope sited at JPL's Table Mountain Facility in Southern California. Slated for first light in late 1999, OCTL will serve a role for optical communications very similar to the

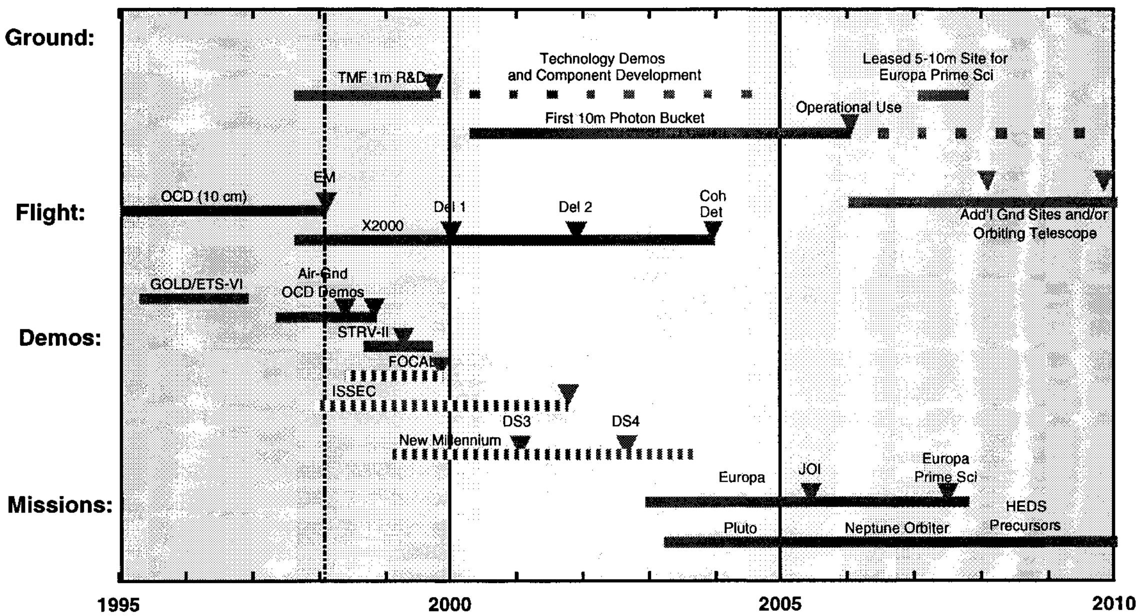

Figure 8: Optical deep space telecommunications roadmap

role played by DSS 13, the DSN's 34m R&D antenna, in the development of the DSN's emerging Ka-band capabilities. Specifically, it will support early demonstrations of optical communications and also provide a testbed for component-level developments ultimately needed for operational deep space optical communications. OCTL will support high slew rates, allowing its use in near-term demonstrations which will likely be conducted from low-Earth orbiting platforms. In the longer term, deep space optical downlinks will require significantly larger apertures. TMOD's roadmap calls for the establishment of a network of 10-meter optical ground stations for deep space support in the latter part of the next decade, timed to the need dates of the first deep space optical links. These non-diffraction-limited ground stations, known as "photon buckets", have lower surface tolerances and hence lower cost relative to 10m-class astronomical telescopes. Each 10m photon bucket would be augmented with a 1m uplink telescope, similar to OCTL, which would provide both an uplink communications signal and an uplink reference beacon observed and used by the spacecraft to accurately point the downlink laser signal. Multiple ground stations would be employed to provide site diversity for mitigating the effects of weather on the optical link.

- *Development of optical flight components:* Building on the successful OCD prototype, NASA has recently embarked on a more ambitious optical transceiver under the X2000 technology program at JPL. This effort will lead to a 30-cm aperture telescope with a 3 W transmitted laser signal, providing uplink (0.53 μ) and downlink (1.06 μ) communications, spatial acquisition and tracking, and two-way ranging functions.

- *Flight Demonstrations:* Over the next two years, TMOD will carry out ground-to-ground and aircraft-to-ground tests of the OCD at Table Mountain, validating the quantitative performance of the system over extended atmospheric path lengths and testing the spatial acquisition and tracking characteristics of both ends of the link. In the longer term, JPL is exploring the possibility of supporting the BMDO-sponsored optical communications experiment on STRV-II, and is studying potential flight demonstrations of the OCD on STS (shuttle) or ISS (space station). Similarly, NASA's New Millennium program could provide an ideal platform for flight demonstration, either in the Earth Orbiter or Deep Space segments of that program. However, a particular concern in the current roadmap is that none of these opportunities is currently committed. Identifying and commiting a flight demonstration of the OCD or the X2000 optical transceiver in the earliest possible time frame will be a top priority in technology program planning over the coming year.

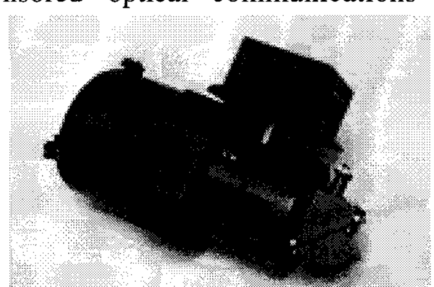

Figure 7: The Optical Communications Demonstrator

Table 1: Data Return (MBytes) for a 5-hr Tracking Pass

	X-band		Ka-band		Optical	
Planet	34m	70m	34m	70m	1m	10m
Mars	182.6	727.5	659.6	1772.1	29.5	2151.3
Jupiter	42.2	168.2	152.5	409.6	6.8	497.3
Saturn	12.5	49.9	45.2	121.4	2.0	147.4
Pluto	0.7	2.9	2.6	7.1	0.1	8.4

Notes:

RF cases referenced to 1m effective s/c antenna, 10 W RF radiated power
Optical cases referenced to 30 cm s/c telescope, 3 W optical transmitted power, l=1.06 m
RF values averaged over complexes; optical assumes Goldstone
RF cases assume 6K CCR HEMT LNA systems
Optical cases averaged over Sun-Earth-Probe (SEP) angle
Optical performance varies w/SEP angle; 10m: +-50% (1m: +-5%) for SEP=180 deg-10deg
All cases referenced to data rate at 30 deg elevation
RF links assume 90% availability; optical assumes 70%; data volume deweighted by availability
No additional link margin included

Flight mission applications: The timing of the optical roadmap, and particularly the implementation of 10m photon buckets, will be driven by the need dates of the first deep space users. One aggressive scenario recently examined assumed that the Europa Orbiter mission (the first launch of the new NASA Outer Planets Program) chooses to fly the X2000-based optical transceiver in order to augment their science return. For one early mission design, the spacecraft would launch in 2003, enter the Jovian system in 2005, and then spend several years maneuvering into orbit about the moon Europa, culminating in a 30-day prime science mission in 2007. In this scenario, early cruise checkout of the optical flight hardware would be supported by the 1m OCTL. The first 10m photon bucket would come online in 2006, one year prior to the Europa prime science phase. In addition, because of the short nature of that prime phase, NASA would look at the possibility of leasing time on a 5-10 meter astronomical telescope to augment this first operational site. Based on the success of this first use, NASA could then add additional 10m ground sites, or alternatively could assess the cost/benefits of establishing a deep space optical relay aperture in earth orbit to get above the detrimental effects of the Earth's atmosphere. Other potential users of optical communications include subsequent Outer Planet program missions such as Pluto Express and Neptune Orbiter, as well as future Mars relay communications orbiters, providing very high-bandwidth "trunk line" communications back to Earth for sophisticated robotic surface rovers and aerobots, and eventually for piloted Mars missions.

4. SUMMARY

The impact of these new technologies can be quantified by revisiting the telecommunications metrics we defined in Section 3.1. First is the simple metric of available DSN tracking time and the anticipated 60% DSN oversubscription based on a projection of the needs of the rapidly expanding mission set using current operations concepts. The Ka-band roadmap provides a path to deal with this demand while simultaneously providing increased science data return to future missions. With network-wide Ka-band support on all 34m BWG antennas by 2003 and the availability of efficient, low-mass, low-cost Ka-band flight components in this same time frame, we assume that Ka-band will be a very viable option for mission in the 2003-2005 time frame and beyond. With the roughly four-fold performance advantage of Ka-band relative to X-band, future missions will be able to adopt a new operations concept which requires a factor of two less DSN tracking time but still provides roughly a factor of two more data volume. In addition, implementation of highly automated DSN ground systems in this time frame will increase available antenna hours by reducing pre-/post-calibration time. A revised DSN loading study, based on the assumption that NASA missions starting in 2005 will use Ka-band to reduce their tracking requirements to one 5-hr pass per week in cruise phase and one 5-hr pass per day in prime science phase (which still provides an overall increase in data volume return), shows that the anticipated mission set can be well-supported with existing DSN assets outfitted with new Ka-band electronics.

Moving to our second metric, of interest to future mission designers is the actual data volume that can be obtained in one of these short, 5-hr tracking passes. Link analyses for X-band, Ka-band, and optical links into various ground assets exhibit the performance gains possible by moving to higher frequencies, as shown in Table 1. (These links represent theoretical upper limits, and do not include additional link margins, allocation of power to residual carriers or ranging channels, etc.; see table notes for detailed assumption. Use these numbers as a guide to the *relative* performance of different configurations.) Several observations can be made: First, these numbers confirm that a 34m Ka-band link is roughly comparable to a 70m X-band link, and nearly four times higher than a 34m X-band link. Second, if the development of adaptive Ka-band feed systems succeeds on the 70m antennas, even higher performance is possible. In fact, the Ka-band/70m link provides performance nearly equivalent to the optical/10m link for the spacecraft configurations considered here.

Finally, we can look at our third metric, aggregate ground network capacity for deep space communications, to view at the highest level how these technology developments will lead to dramatic increase in the bandwidth available for supporting fleets of robotic and, ultimately, piloted missions in the new millennium. Figure 9 shows the growth of this aggregate communications capacity metric at S-band, X-band, Ka-band, and optical between now and 2010, based on the technology roadmaps presented here. Again, several observations can be made: First, the use of new turbo codes as well as planned improvements in our current feed systems will lead to continuous incremental growth of our existing X-band capability. Second, the proposed Ka-band implementations provide much more dramatic growth. The Ka-band capability of just the five BWG antennas will outperform the entire DSN at X-band, and with the addition of Ka to the HEF and 70m antennas, the resulting Ka-band capability will be more than four times our current X-band capacity. Finally, optical provides a long-range path to future growth. The first optical 10m station will offer roughly the performance of today's entire DSN capacity.

In conclusion, new RF and optical technologies are poised to provide breakthrough increases in NASA deep space telecommunications capacity, allowing NASA to meet the needs of a growing and increasingly challenging mission set while offering increased data return to individual missions. In the near term, the addition of Ka-band capabilities to existing DSN antennas is an extremetly cost-effective way to increase capacity. In the longer term, optical communications appears to be the path for future growth. Achieving this growth will require a coordinated

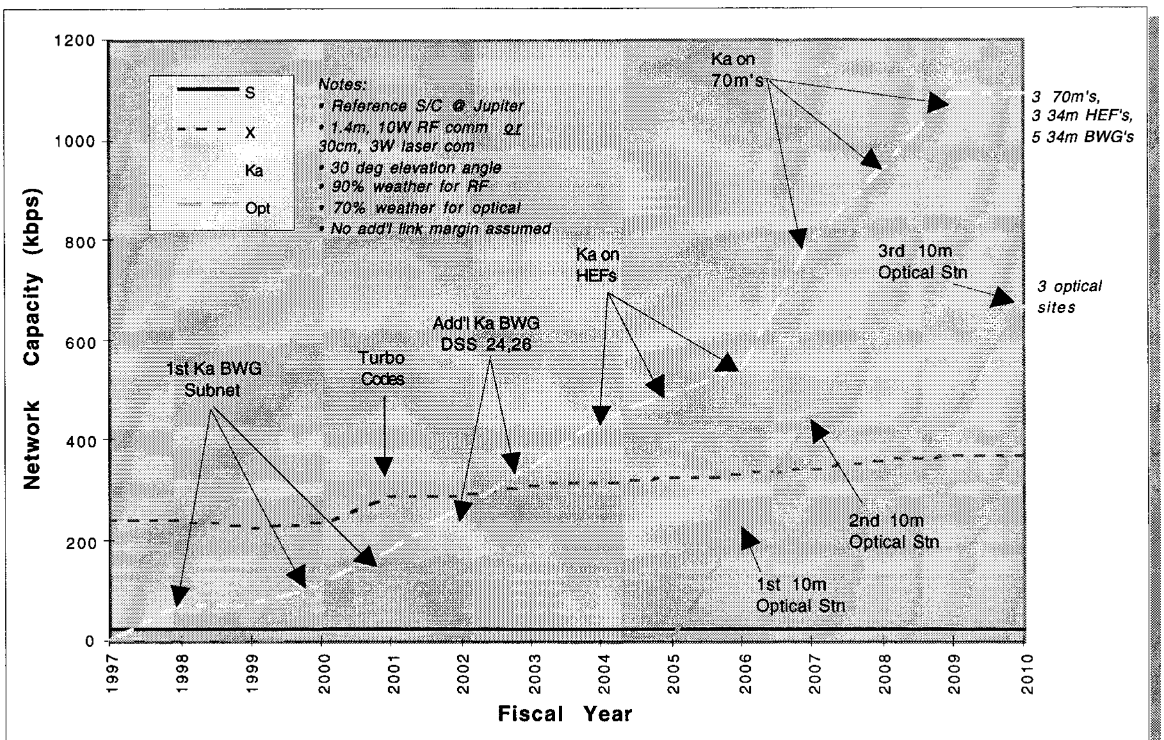

Figure 9: Projected growth in NASA's deep space communications capability based on new RF and optical communications technologies.

approach towards the development of flight and ground technologies. Critical items on the roadmaps include the need for improved efficiency of Ka-band spacecraft amplifiers, understanding the potential performance of the 70m antennas at Ka-band, and establishing one or more near-term optical flight demonstrations.

5. ACKNOWLEDGEMENTS

The work reported here reflects contributions from many people at JPL. The authors especially thank Gael Squibb, Rich Miller, Steve Townes, Jim Layland, Jeff Osman, Chris Yung, Mark Gatti, Jim Lesh, Keith Wilson, Hamid Hemmati, David Rochblatt, Javier Bautista, Sam Petty, Bob Clauss, Steve Slobin, Shervin Shambayati, Fabrizio Pollara, and Anil Kantak for valuable inputs and discussions in developing this roadmap.

The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronatutics and Space Administration.

6. REFERENCES

Butman, S., D. Morabito, A. Mittskus, J. Border, J. Berner, C. Whetsel, M. Gatti, C. Foster, V. Vilnrotter, H. Cooper, A. Del Castillo, A. Kwok, J. Weese, M. Speranza, R. Davis, W. Adams, A. McMechen, C. Goodson, G. Bury, D. Recce, "The Mars Global Surveyor Ka-band Link Experiment (MGS/KaBLE-II)", Proceedings of the Third Ka Band Utilization Conference, pp 179-186, Sorrento, Italy, September 15-18, 1997.

Divsalar, D. and F. Pollara, "On the Design of Turbo Codes", The Telecommunications and Data Acquisition Progress Report 42-123, July-September 1995, November 15, 1995 (http://tda.jpl.nasa.gov/tda/progress_report/).

Edwards, C., L. Deutsch, M. Gatti, J. Layland, J. Perret, and C. Stelzried, "The Status of Ka-band Communications for Future Deep Space Missions," Proceedings of the Third Ka Band Utilization Conference, pp 219-225, Sorrento, Italy, September 15-18, 1997.

Hemmati H., K. Wilson, M. K. Sue, L. J. Harcke, M. Wilhelm, C.-C. Chen, J. R. Lesh, Y. Feria, D. Rascoe, F. Lansing, and J. W. Layland Comparative Study of Optical and Radio-Frequency Communication Systems for a Deep-Space Mission, The Telecommunications and Data Acquisition Progress Report 42-128, October-December 1996, February 15, 1997 (http://tda.jpl.nasa.gov/tda/progress_report/).

Lo, V. Y., "Ka-Band Monopulse Antenna-Pointing Systems Analysis and Simulation", The Telecommunications and Data Acquisition Progress Report 42-124, October-December 1995, February 15, 1996 (http://tda.jpl.nasa.gov/tda/progress_report/).

Morabito, D. D., "The Efficiency Characterization of the DSS-13 34-Meter Beam-Waveguide Antenna at Ka-Band (32.0 and 33.7 GHz) and X-Band (8.4GHz)", The Telecommunications and Data Acquisition Progress Report 42-125, January-March 1996, May 15, 1996 (http://tda.jpl.nasa.gov/tda/progress_report/).

National Aeronautics and Space Administration, "NASA Strategic Plan", NASA Policy Directive (NPD)-1000.1, Washington, DC, 1998.

National Research Council, Committee on Advanced Space Technology, Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems, "Space Technology for the New Century," National Academy Press, Washington, DC, 1998.

Rengarajan, S. R., Imbriale, W. A. and Cramer, P. W., Design of a Deformed Flat Plate to Compensate the Gain Loss Due to the Gravity-Induced Surface Distortion of Large Reflector Antennas, URSI Commission B 1998 Electromagnetic Theory Symposium, Thessaloniki, Greece, May 25-28, 1998.

Rebold, T. A., A. Kowk, G. D. Wood, and S. Butman, "The Mars Observer Ka-band Link Experiment," The Telecommunications and Data Acquisition Progress Report 42-117, vol. January-March 1994, Jet Propulsion Laboratory, Pasadena, California, May 15, 1994.

Riley, A. L., S. Kayalar, A. Mittskus, D. Antsos, E. Grigorian, E. Olson, J. Neal, E. Satorius, and A. Kermode, "New Millennium Deep Space Tiny Transmitter: First Phase of a Digital Transponder," Proceedings of the AIAA/IEEE Digital Avionics Systems Conference, Atlanta, Georgia, pp 225-230, October 27-31, 1996.

Vilnrotter, V., and B. Iijima, "Analysis of Array Feed Combining Performance Using Recorded Data", The Telecommunications and Data Acquisition Progress Report 42-125, January-March 1996, May 15, 1996 (http://tda.jpl.nasa.gov/tda/progress_report/).

Wilson, K. E., and J. R. Lesh, "An Overview of the Galileo Optical Experiment (GOPEX)," The Telecommunications and Data Acquisition Progress Report 42-114, April-June 1993, pp. 192-204, August 15, 1993.

Wilson, K. E., J. R. Lesh, K. Araki, Y. Arimoto, "Overview of the Ground-to-Orbit Lasercom Demo," Free-Space Laser Communication Technologies IX, Proceedings of SPIE, vol. 2990, pp 23-30, San Jose, California, 13-14 February, 1997.

Yan, Tsun-Yee, Methu Jeganathan, and James Lesh, "Progress on the Development of the Optical Communications Demonstrator," Free-Space Laser Communication Technologies IX, Proceedings of SPIE, vol. 2990, p 94, San Jose, California, 13-14 February, 1997